CROSS-STRIKE STRUCTURAL DISCONTINUITIES: POSSIBLE EXPLORATION TOOL FOR NATURAL GAS IN APPALACHIAN OVERTHRUST BELT

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Cross-Strike Structural Discontinuities: Possible Exploration Tool for Natural Gas in Appalachian Overthrust Belt[1]

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Abstract Cross-strike structural discontinuities (CSD's) are broad, diffuse, transverse zones of structural disruption in the Appalachian and other overthrust belts. At Parsons and Petersburg, eastern West Virginia, CSD's are 8 to 10 km wide. Folds of various scales, longitudinal faults, and unmodeled gravity anomalies terminate or change style across or within the two CSD's. Both CSD's are visible on Landsat images. Wherever tested, CSD's contain larger or more abundant joints, normal faults, or both, than do surrounding areas. Mapping usually reveals little displacement across transverse faults that parallel or lie in some CSD's. The CSD's appear to have divided the detached sedimentary prism into quasi-independent structural blocks. Median values of sizes and spacings of the Parsons, Petersburg, and nine other Appalachian CSD's suggest that each CSD contains about 980 cu km of intensely fractured rock, and that CSD's constitute about 14% of the detached sedimentary rocks. CSD's and their extensions into the foreland can be loci of exploration in gas-producing fractured Devonian clastic rocks of the Appalachian basin. Many short air photo lineaments are surface expressions of fractures or fracture zones. Wells should be sited at intersections of short air photo lineaments in the CSD's.

PURPOSE

This paper suggests an exploration strategy for natural gas in part of the central Appalachian Plateau province, using CSD's. The target is fracture porosity and fracture permeability in Middle and Upper Devonian clastic rocks (mostly shales), parts of which have been profitable or marginally profitable producers since the early 1900s (Shumaker and Overbey, 1976; Wheeler et al, 1976a; Schott et al, 1978; Anonymous, 1978; Dean and Overbey, 1978; Aguilera and van Poollen, 1979; Barlow, 1979). The purpose of this paper is to suggest an exploration method for structural traps in unexplored or presently unproductive areas beyond the region of present commercial production in eastern Kentucky and adjacent states. The suggested method predicts subsurface locations of large drillable volumes of intensely jointed rock in the Plateau province by combining (1) observations and theories about major, cross-strike structural discontinuities, (2) observations of short air photo lineaments, and (3) understanding of detachment tectonics in the central Appalachians. Each application of the method suggested here requires local evaluation of four assumptions about orientations, depths, permeabilities, and seals of fracture systems. The assumptions are discussed in a following section.

CROSS-STRIKE STRUCTURAL DISCONTINUITIES

Characteristics

Overthrust belts in several orogenes contain large, cross-strike structural discontinuities (CSD's): structural lineaments or alignments, at high angles to regional strikes, that are recognizable because they disrupt strike-parallel structural, geophysical, geomorphic, sedimentologic, or other patterns. Characteristics of individual CSD's vary. Some characteristics are summarized in the following paragraphs, and described in detail in the references cited there and by Wheeler et al (1979). Types of data that have been used to recognize various CSD's are listed in the Appendix. One of the most common traits is alignment of bends, noses, and style changes of detached map-scale folds. However, most such disruption of folds is neither sharp enough, systematic enough in apparent senses of offset, nor of low enough magnitude to be explained by the few small transverse faults that are sometimes found by mapping. A common inference is that CSD's mark diffuse boundaries between blocks that were partly decoupled during thrusting, so that the blocks moved together, but in part were deformed independently (Rodgers, 1963; Gwinn,

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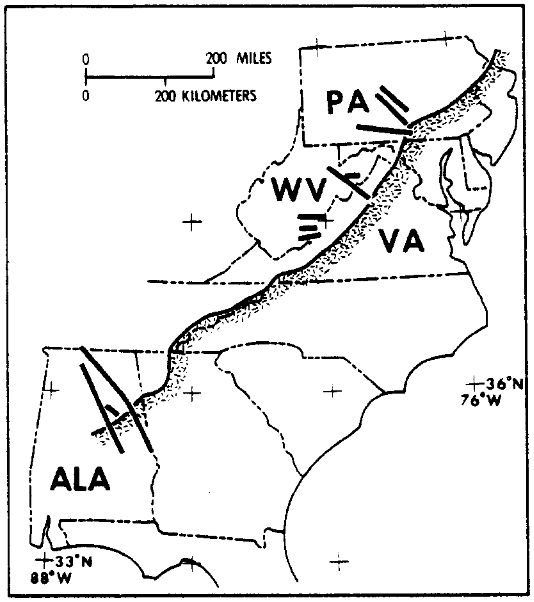

FIG. 1—Eleven Appalachian cross-strike structural discontinuities (CSD's). Heavy solid lines: CSD's. Medium-weight solid line and pattern: approximate northwest limit of exposed metamorphic and igneous rocks. Approximate locations of discontinuities are from Drahovzal (1976), Gold and Parizek (1976), Sites (1978), Dean et al (1979), Dixon (1979), and T. Wilson (unpub. data). To my knowledge only four areas have been explored for CSD's: Alabama, Pennsylvania, and parts of northeast and southeast West Virginia.

1964). Often it is further inferred that the decoupling occurred along zones of prethrusting weakness in the thrust sheets—fracture zones propagated upward from basement faults underlying the thrusts (Kowalik, 1975), or formed at vertically stacked facies changes (Trumbo, 1976). To my knowledge those two inferences, although attractive, have not yet been tested on enough CSD's to be regarded as generally valid. This paper requires only a descriptive characterization of CSD's, and not understanding of their origin.

Wheeler et al (1979) summarized sizes and characteristics of 15 CSD's or groups of CSD's in the Appalachians, Ireland, and southern Chile, and cited references describing similar structures in the Canadian Rocky Mountains. Eleven Appalachian CSD's have been mapped and studied in Pennsylvania, West Virginia, and Alabama (Figs. 1, 2). These CSD's are larger and more complex than simple tear faults, fault zones, or joint zones. Using the data summarized for three orogenes by Wheeler et al (1979), CSD's can be estimated to be typically about 3.5 km wide, at least 4 km deep, and at least 70 km long, with a centerline spacing of about 25 km (Fig. 3). Such CSD's would each contain at least 980 cu km of rock, and, therefore, could include 14% of that part of the detached sedimentary prism that they traverse. Thus, CSD's can be major and fundamental parts of the architecture of an overthrust belt and as volumetrically important as most longitudinal folds.

In addition, Podwysocki et al (1979; oral com-

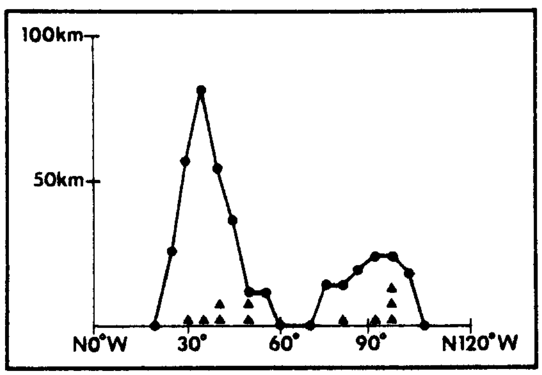

FIG. 2—Orientations of 11 west- or northwest-trending CSD's that are shown in Figure 1. Orientations are in degrees west of north. Triangles show orientations of individual CSD's. Solid line with dots shows kilometers of CSD length, smoothed as three-term moving average (Davis, 1973, p. 223) at 5° intervals. Both representations show that Appalachian CSD's are not perpendicular to regional strikes. Instead they have two preferred orientations. Alabama CSD's are closer to perpendicularity than are those of central Appalachians (see Fig. 1).

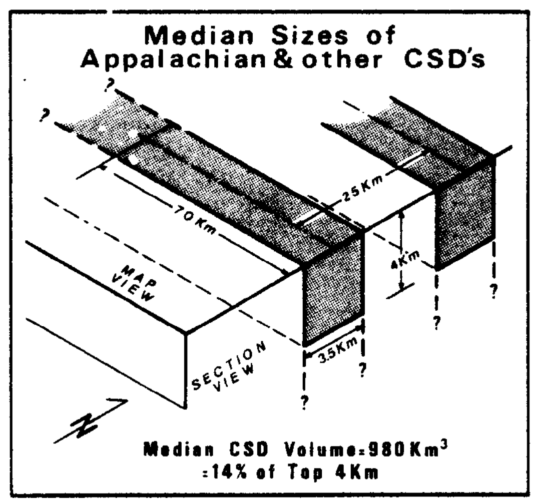

FIG. 3—Median sizes of Appalachian and other CSD's (data from Wheeler et al, 1979). Stippled areas represent ends and tops of rock volumes in individual CSD's.

mun., 1978, 1979) are mapping two CSD's or probable CSD's in south-central New York State and north-central Pennsylvania. In the overthrust belt of northwestern Montana, Mudge (his Fig. 4 and p. B9-B10 of 1972b) described the Scapegoat-Bannatyne trend, a northeast-trending alignment of structural and stratigraphic anomalies identified on the craton east of the overthrust belt, and perhaps in the easternmost thrusts (Dobbin and Erdmann, 1955). The cratonic part of the Scapegoat-Bannatyne trend could have a CSD overlying its extension into the thrusts, and indeed Ross et al (1955) and Dobbin and Erdmann (1955) showed two northeast-striking, apparently high-angle faults where the trend intersects the thrusts. Northwest of the Scapegoat-Bannatyne trend, Mudge (1972a, Pl. 1) mapped imbricate thrusts. His map shows that the thrust sheets contain numerous fold noses, tear faults, and ends of individual thrust slices or thrust complexes, some of which appear to align to form one or more northeast-trending CSD's. In western New York State, Dunn et al (1979, p. 134) suggested that the north-striking Clarendon-Linden fault may be a CSD; if the fault extends south under the Appalachian thrusts and disrupts them, then the term is justified in the thrust belt, but not north of the thrusts, because the term CSD should be restricted to the detached prism of rocks (see next subsection).

Terminology

Three points of terminology have caused confusion and merit explanation.

1. From experience in mapping and discussing known and possible CSD's, it seems advisable to restrict use of the term cross-strike structural discontinuity to detached rocks in thrust belts: a CSD is a structural lineament, defined by disruptions in the strike-parallel patterns of folds, faults, and their various geologic, geophysical, and other signatures, and consists of those disruptions, both on a map and in three dimensions. The cause of the disruptions may not be known, but their existence, alignment, and properties are usually clear. In particular, if a CSD is found or thought to overlie a high-angle basement fault that parallels the CSD, the fault should be given its own name to eliminate confusion. This is especially appropriate if the fault extends beyond the edge of the thrust belt, and thus beyond the CSD, into the undetached foreland.

2. It has proven useful to distinguish CSD's clearly from other types of lineaments, particularly large imagery lineaments, and that is the reason for introducing a new descriptive term in this paper. Many CSD's are recognized in more kinds of data than are imagery lineaments. CSD's can contain one or more imagery lineaments of various kinds and sizes along part or all of the lengths of the CSD's, but in general CSD's are wider and better defined and mapped. This paper distinguishes three kinds of lineaments: CSD's, Landsat lineaments, and short air photo lineaments.

3. This paper distinguishes joints and faults, and the term fracture refers collectively to joints, faults, both, and other cracks of known or unknown origin.

Parsons and Petersburg Lineaments

In northeast West Virginia, the Parsons and Petersburg structural lineaments are two CSD's that contain structurally disrupted rock (Fig. 4; see references given by Wheeler et al, 1979). Parts or aspects of the Parsons lineament were detected by Gwinn (1964), Woodward (1968), and Rodgers (1970, Pl. 1A). Mapping and other work have since defined the Parsons lineament as a N50°W-trending feature at least 55 km long, 10 km wide, and at least 3 km deep. Part of the lineament appears clearly on Landsat images. Major folds and longitudinal reverse faults, intermediate-scale folds, and outcrop-scale folds associated with southeast-dipping shear zones terminate or change abundance, size, shape, or orientation across or within the Parsons lineament. Some characteristics of the lineament are shown in Figure 5 as an example of the complex expression of a CSD. Bends and terminations of axial traces of folds on the "Geologic Map of West Virginia" (Cardwell et al, 1968) are suggestive of a possible

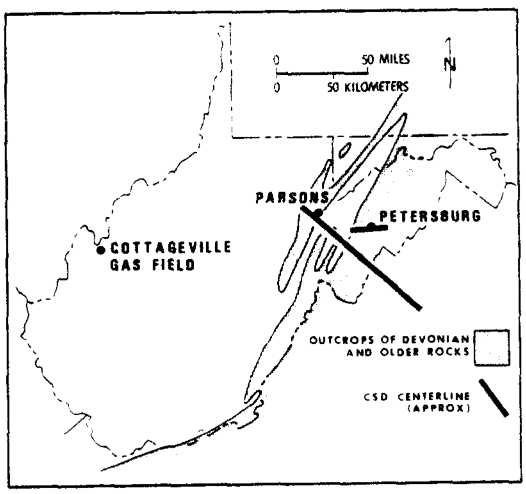

FIG. 4—Index map of West Virginia. Most production from fractured Devonian shaly rocks is within, south, and west of Cottageville field.

extension of the Parsons lineament northwest nearly to the Ohio River. Mapping by T. Wilson (unpub.) and Rader and Perry (1976) is more consistent with the lineament extending to the southeast through the Valley and Ridge province. Thus, the total speculated length of the Parsons lineament is about 250 km.

Woodward (1968) noted part of the Petersburg lineament. Mapping and other work have since defined the lineament as trending about N85°E through Petersburg, and as at least 80 km long, 8 km wide, and at least 5 km deep. The Petersburg lineament has the same effects on folds and faults of various scales as does the Parsons lineament. The Petersburg lineament appears clearly on Landsat images. Sites (1978) speculated that its total length may be 160 to 320 km.

The Parsons lineament extends northwest and southeast an indeterminate distance beyond the area of Figure 5, but the data shown there illustrate three points about CSD's: (1) CSD boundaries can be diffuse; different data types can show disrupted patterns of anomalies, in zones of different widths and different but largely overlapping positions; (2) CSD's can be ill-defined and of unknown origin, but real, with disruption of map-scale structure expressed in several ways; (3) although CSD's and Landsat lineaments may coincide or nearly coincide, they are not the same things. The Parsons and Landsat lineaments have

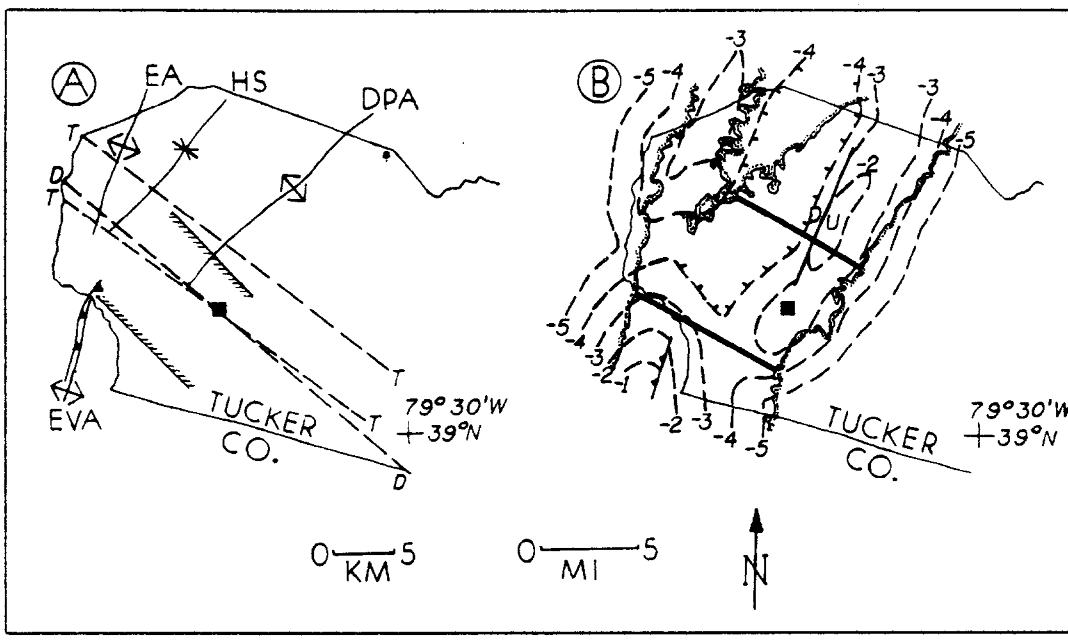

FIG. 5—Selected aspects of structure of part of Parsons lineament, where it crosses Devonian clastic rocks exposed in cores of anticlines in western Tucker County, northeastern West Virginia (see Fig. 4 for index map). For details of these and other related data, see Dixon (1979), Wheeler et al (1979), and other references cited in text. Solid square is town of Parsons.

A, Dashed lines locate three Landsat lineaments drawn by Trumbo (1976, marked *T*) and Dixon (1979, marked *D*). Solid lines show axial traces of four detached folds and outcrop of one thrust fault (teeth on top block), from Cardwell et al (1968). *EA*, Etam anticline; *HS*, Hannasville syncline; *DPA*, Deer Park anticline; *EVA*, Elkins Valley anticline. Fault and all folds but *HS* extend northeast or southwest beyond map area. Hachured lines show northeast and southwest borders of area of unusually high joint intensity, simplified from Dixon (1979).

B, Wiggly solid lines show outcrop of contact of Upper Devonian clastic rocks of Chemung Group with overlying uppermost Devonian red beds of Hampshire Formation, stippled on young side of contact (simplified from Cardwell et al, 1968). Contact outlines four folds named in A. Dashed lines are structure contours atop Middle Devonian Onesquethaw Group, underlying Devonian shaly sequence, from Cardwell (1973). Contours are in thousands of feet (0.3 km) below sea level. Hachures point inward in Hannasville syncline. Ground elevation is 460 to 760 m in most of map area. Along Deer Park and Elkins Valley anticlines in Tucker County are numerous upright folds with near-zero plunges, northeast-trending axial traces several kilometers long, and wavelengths of about 400 m. Two heavy solid lines show bounds of area of unusual abundance of these mapped folds, and most of their axial traces bend or stop at heavy lines.

different widths, positions, and orientations.

Depths

There are few depth estimates for CSD's. Similarly, it is unclear whether or not the structural disruptions that comprise the Parsons and Petersburg lineaments extend below the deepest detached strata to involve the basement.

In West Virginia, depth estimates are based on several lines of evidence. (1) Map-scale folds and faults within the thrust sheets may change position, style, or orientation across a CSD. Such changes are usually inferred from surface mapping, gravity data (see next paragraph for an example), and balanced cross sections constructed from surface, well, gravity, and seismic data. (2) Such changes in detached structure across a CSD require that the CSD extend at least as deep as the deepest detachment involved in those changes. The deepest detachment of all is usually in Middle Ordovician or Lower Cambrian shales that can lie as deep as about 7.3 km below ground level where the Parsons and Petersburg lineaments cross the westernmost Valley and Ridge province (Perry, 1971, p. 186; Sites, 1978, p. 110). (3) If all observed characteristics of a CSD can be explained by structures within the thrust sheets, and if there is no evidence for a change in basement structure or in depth to basement across the CSD, then it is reasonable and conservative to assume that the CSD does not cut basement there.

I know of no evidence requiring the Parsons or Petersburg lineaments to extend deeper than the basal detachment (Lower Cambrian shale) in the Plateau or western Valley and Ridge provinces. Unmodeled, strike-parallel anomalies in residuals from terrane-corrected Bouguer gravity data terminate at both structural lineaments (Kulander and Dean, 1976, 1978a). Kulander and Dean concluded that the anomalies are caused by structural duplication of high-density Lower Devonian and Silurian, or Cambrian and Ordovician limestones and dolomites, and that the terminations of the anomalies along strike occur where such structural duplication ends. Those ends occur where underlying detachments step up along strike to higher structural and stratigraphic levels, in the manner suggested by Gwinn (1964) and figured by Harris (1970). Kulander and Dean (1978a) mapped unmodeled magnetic anomalies, and attributed them to susceptibility differences in the metamorphic and igneous rocks beneath the thrusts. Their total-intensity magnetic map does not appear to me or to Kulander (oral commun., 1978) to show that those susceptibility differences are caused by cross-strike faults in the subthrust metamorphic and igneous rocks, at least in the Plateau and western Valley and Ridge provinces of northern and central West Virginia. Balanced cross sections controlled by surface mapping and subsurface data (Perry, 1971, 1975; Sites, 1978) northeast and southwest of the Petersburg lineament in the western Valley and Ridge province show no evidence for abrupt change along strike in basement depth or in structure below the Middle Ordovician shales.

However, farther east, closer to the orogenic core, one or both lineaments may well extend below the deepest detachment. On the southeast the magnetic map of Kulander and Dean (1978a) shows magnetic relief of about 300 g across the southeastward extension of the Parsons lineament into Rockingham County, Virginia, in the eastern Valley and Ridge province. Pilant and Robison (1977) mapped magnetic lineaments in the Piedmont province of Virginia. Their magnetic lineaments parallel the Parsons lineament, and the northeasternmost lineament is on trend with the Parsons lineament (W. Pilant, oral and written commun., 1977). Further, in southeast West Virginia, Pennsylvania, Alabama, Chile, and Ireland, CSD's resembling the Parsons and Petersburg lineaments either extend into exposed metamorphic and igneous rocks, include volcanic centers or metal deposits, pass through saddles or abrupt terminations of magnetic anomalies, or contain faults of long-term activity and changing senses of slip (see work referenced by Root and Hoskins, 1977; Wheeler et al, 1979). Finally, Wheeler (unpub.) examined the orientations and minimum lengths of CSD's as a class, and concluded that orientations and lengths were probably more influenced by cratonic structures activated or reactivated under advancing detached blocks, than by structural processes originating within the thrust sheets.

Thus in the areas cited, wherever data allow a test for basement involvement, CSD's have been shown or interpreted to overlie now, or to have formed over and later been thrust away from, basement faults that are also at high angles to regional strike. That may be true of CSD's generally, and such a generalization is the main reason one might assume any basement involvement for the mapped parts of the Parsons and Petersburg lineaments. Data are lacking for a test of basement involvement in either lineament.

Thus the question of basement involvement in the Parsons and Petersburg lineaments remains unanswered. However, CSD's are complex structures, and may form in more ways than one; Wheeler (1978b, p. 26, 27) postulated a mechanism for forming aligned tear faults and anticlinal noses without basement involvement, by processes operating entirely within the thrust sheets.

Whether a particular part of a specific CSD overlies or once overlay basement faults is a question answerable only with local data. That question will arise again in a later section on "Effect of Detachment," and its answer for a particular area will determine the western limit of applicability of the exploration strategy suggested in this paper.

Fractures

Neither the Parsons nor the Petersburg lineament exhibits significant transverse faults; the lineaments are not fault zones, because they do not expose sufficiently large faults, or faults with enough cumulative slip, to explain more than a small part of the lineaments' disruptions of map-scale detached structures. However, they do contain intensely jointed rock. Holland and Wheeler (1977), Dixon (1979), and LaCaze and Wheeler (1979) found that systematic joints are larger, more abundant, or both inside the lineaments than in the same rocks adjacent to the lineaments. Small mappable normal and strike-slip faults and longitudinal joints are more abundant within the Petersburg lineament than northeast or southwest of it in the same stratigraphic units (McColloch, 1976; R. Williams, oral commun., 1976; Sites, 1978). Finally, the combined results of LaCaze and Wheeler (1979) and Dixon (1979) show that the increased joint intensity within the Petersburg lineament occurs in exposed Middle Devonian to Lower Pennsylvanian conglomerates, sandstones, siltstones, and shales, with various dips and extending through approximately 0.8 km of topographic relief down the Allegheny Front. Such a large vertical extent and such insensitivity to changes in dip or lithology make it unlikely that the increased joint intensity associated with CSD's is a near-surface phenomenon.

In summary, I suggest that CSD's like the Parsons and Petersburg structural lineaments contain very large volumes of intensely jointed rock that extend at least as deep as the basal detachment under the Plateau and western Valley and Ridge provinces, and therefore, the CSD's are promising rock volumes in which to seek fractured gas reservoirs. The questions of seals and permeability of such jointed rocks are crucial, and are discussed in a following section on assumptions.

SHORT PHOTOLINEAMENTS

Lattman (1958) defined photogeologic fracture traces as air photo lineaments less than 1.6 km long, and suggested that they are traces of joints or small faults. Since then, many geologists have used the working hypothesis that short photolineaments up to several kilometers long are geomorphic expressions of vertical or nearly vertical zones of unusually fractured rock: joints or joint zones, or small faults or fault zones. The hypothesis is usually tested either by field examination of exposures in the photolineament, or by statistical tests to determine whether water wells on or near the photolineament have significantly higher yields than do wells off or far from the photolineament (e.g., Gold and Parizek, 1976). In and near the Cottageville gas field, which produces from Devonian shales in western West Virginia (Fig. 4), Jones and Rauch (1978) found higher yields in water wells within 30 m of lineaments mapped on low-altitude aerial photographs, and higher natural initial open flows in gas wells within 0.8 km of west-northwest trending, short, air photo lineaments. Beebe and Rauch (1979) found analogous results, including high final (after fracturing) open flows, in the Midway-Extra field, about 32 km south of Cottageville. D. A. Steffy (unpub. data, 1976) found a similar result for water wells in outcropping Devonian sandstones, siltstones, and mudstones near Parsons, and Howard et al (1979) reported similarities for cumulative gas production in eastern Kentucky.

The gas-bearing Devonian clastic rocks are about 0.6 to 1.4 km below ground level in the gas fields of western West Virginia and eastern Kentucky. Eastern equivalents of those rocks are about 0.4 to 2.3 km below ground level in the eastern Plateau province (Cardwell, 1973; Wallace and de Witt, 1975; Patchen, 1977). In most areas, the lower part of the Devonian shaly sequence is the most productive. Therefore, to use short photolineaments as an exploration tool for fractured reservoirs in the Devonian rocks and their eastern equivalents, I make the assumptions of the next section.

ASSUMPTIONS

The exploration strategy suggested in this paper makes four assumptions. In each area for which this strategy is considered, the assumptions should be tested anew against local geologic and other data, because the validity of the assumptions can be strongly affected by local conditions.

I assume (1) that the fractures that probably underlie short photolineaments form vertical fracture zones, and (2) that the depths of the fracture zones approximate the lengths.

Two more assumptions are necessary, and also apply to the fracture zones in CSD's: (3) that the fracture zones are not rendered impermeable in potential reservoir rocks by fault gouge, slickensides, or mineralized joints, and (4) that the fracture zones have retained an intact seal above their permeable portions, perhaps composed of one or more of the following: poorly fractured shale, gouge or slickensides formed on overlying detachment faults and their subsidiary faults, or tightly filled joints.

If those four assumptions are correct, then air photo lineaments one to several kilometers long overlie attractive zones of fracture porosity and fracture permeability in and above the Devonian shaly sequence. More attractive still are intersections of two or more such photolineaments, particularly if the intersections lie in CSD's. Assumption 1 is the most likely to be generally true, on the basis of scattered unpublished observations by several workers on large natural and artificial exposures. Gold et al (1973, p. 129) also made assumption 2 without giving supporting evidence. Assumption 2 is valid enough for the purposes of this paper if the fracture zones beneath short photolineaments have depths of about half the lengths of the photolineaments, or greater. Short photolineaments have been used as suggested here in the Appalachian basin with some success. For example, Ryan (1976) used them successfully at depths of about 1.2 km, although many of his photolineaments are tear faults rather than joint zones. If assumption 2 fails in a particular area, then instead of seeking individual photolineaments and their intersections, one might seek small subareas with high densities of short photolineaments and intersections. Assumption 2 would then be replaced by assuming that the high fracture density of such a subarea extends deeper than do the individual fractures or fracture zones under single short photolineaments.

Assumptions 3 and 4 require a balance of factors that can vary widely from area to area, but five observations make the two assumptions seem at least plausible. (1) Where examined at the surface, the increased fracture intensity in the Parsons and Petersburg lineaments is caused by joints, partly unmineralized, and not by faults with gouge or slickensides. (2) The dark shales in the lower part of the Devonian clastic sequence that form the main source rock and the fractured reservoir contain abundant small faults, folds, slickensides, gouge zones, and fractures of varied mineralization and natural propping, in both exposure and cores (Woodward, 1943; Vinopal et al, 1979; Evans, 1980); yet the dark shales have enough natural permeability that drillers often lose circulation in them (L. Woodfork, oral commun., 1974) and they are used for subsurface injection of brines and industrial liquid wastes (Hidalgo et al, 1974). (3) Dixon (1979) traced the zones of high joint intensity of the Parsons and Petersburg lineaments about 24 km northwest and west, respectively, of exposed Devonian rocks. There, where most of the dark Devonian shales are 2.0 to 2.3 km below ground level (T. Wilson, written commun., 1979), the joint intensity at ground level drops abruptly to normal levels. The joint systems of the two lineaments may stop there, but it is equally likely that they continue westward, sealed beneath the cover of comparatively unfractured Pennsylvanian rocks. (4) In the area where Dixon worked, 373 wells drilled for gas since 1972 were classified as producers, wells with gas shows, or dry holes. A slightly higher ratio of dry holes to producers occurs where Dixon mapped high joint intensity in the Parsons and Petersburg lineaments. This ratio supports the suggestion that permeable fracture systems of significant vertical extent degassed through partial or broken seals where Dixon worked, but may be sealed farther west, where overburden is thicker or conditions are otherwise favorable. (5) Beebe and Rauch (1979) suggested that high bicarbonate concentrations in water wells near high-yielding gas wells are caused by near-surface oxidation of methane, which migrated up along fractures from underlying dark Devonian shales. Their suggestion indicates that permeable fracture systems of significant vertical extent can be consistent with effective seals.

Thus none of the assumptions seems unreasonable, but I know of no information that would clearly support or contradict any of them and would also apply to large parts of the Appalachian basin. The assumptions should be evaluated for each area under consideration, using local data. Further attempts at a general evaluation seem unwise. Wheeler (1978b) attempted such a local application.

EFFECTS OF DETACHMENT

As explained in the section defining CSD's and describing the Parsons and Petersburg lineaments, some CSD's have been shown to have formed over basement faults. The clearest example of which I am aware in the Appalachian basin is the Everett-Bedford lineament, the southernmost CSD shown in Pennsylvania in Figure 1 (see references cited by Wheeler et al, 1979, for details). The Everett-Bedford lineament is now known to be part of the Transylvania fault zone of Root and Hoskins (1977). For some other CSD's there is insufficient evidence to decide whether or not basement is involved. The known CSD's in West Virginia, including the Parsons and Petersburg lineaments, are of this type so far.

The exploration strategy suggested in this paper has two versions, according to whether or not basement is known or assumed to be involved in a particular CSD. First, a particular CSD may overlie a basement fault. The fractures characteristic of the CSD, whether unusually intense joint systems, locally developed faults, or both, probably formed as brittle deformation propagated upward from the basement fault through the overlying sedimentary cover. Then the thrusts will not limit the fracture systems of the CSD. The fracture systems will extend below the deepest thrust. If the basement fault extends farther toward the craton than do the outermost thrusts, so may the fracture systems of the CSD. In West Virginia, CSD's could be regarded as containing potential fractured reservoirs as far west as one could trace them. In particular, CSD's regarded as having had basement involvement could help guide exploration in areas near present production from the Devonian shaly sequence, mostly in southwestern West Virginia and eastern Kentucky (Fig. 4).

Second, one could take the more conservative position that, because CSD's are complex and no basement involvement has been demonstrated for CSD's in West Virginia, those CSD's formed entirely within the thrust sheets. Then the fracture systems characteristic of CSD's like the Parsons and Petersburg lineaments should be restricted to areas where the possible reservoir rocks are detached. For that reason, Wheeler (1978a) originally conservatively restricted application of this paper's exploration strategy to the area east of the subsurface line where the deepest detachment cuts upward into the Devonian shaly sequence. That line runs along the Mann Mountain anticline in south-central West Virginia (Perry and Wilson, 1977; Perry, 1978) and along or just west of the Burning Springs anticline in west-central West Virginia (Rodgers, 1963, 1970, p. 19-21; Cardwell et al, 1968), and omits the area of present production from the Devonian shaly sequence (Fig. 4). In this second, conservative version of the exploration strategy, present production from undetached rocks in and near Cottageville and eastern Kentucky would be from fracture systems not associated with CSD's. This more conservative approach is illustrated in Figure 6.

Strictly speaking there is yet a third possibility: that a particular CSD formed over a basement fault but has since been thrust away from it on a major detachment. Then the fracture systems now associated with the shallow, visible part of the CSD would not extend below the detachment. The deeper, beheaded part of the CSD would constitute a major fracture system, perhaps sealed by the gouge and slickensided shales of the overlying detachment zone. However, that fracture system would be blind, buried under and hidden by unrelated surface structures, lying an unknown distance east of the visible part of the CSD. Until methods for estimating transport distances of thrusts achieve greater accuracy and precision, it seems unlikely that the deep, blind parts of such CSD's could be found and recognized. This third possibility is probably indistinguishable from the second. Both can be treated with the second, more conservative version of the exploration strategy, in which CSD's and their fracture systems are regarded as thrust bounded at the ends toward the craton and on the bottoms.

In the absence of regionally usable guidelines as to whether a particular CSD has basement involvement, or is thrust bounded, the western limit of application of the approach suggested in this paper is likely to depend on locally available data about basement and shallower subsurface structure, and on the economics and acceptable risks of a particular exploration or drilling program.

Whether one takes the conservative or the optimistic view of the westward extents of CSD's and their associated fracture systems, there are other potentially complicating effects of detachment. It seems likely that the orientations, locations, or both, of high-angle fracture zones are different below than above a detachment fault: as already described, fracture zones formed before the detachment would be beheaded, with tops no longer above or connected to bottoms. Fracture zones formed during or after detachment may change orientation, size, or position across the detachment, to reflect differing magnitudes and orientations of stresses in the two regimes. For example, E. Werner (oral commun., 1978) found differences in orientations and other characteristics of systematic joints across the probable outcrop of a southeast-dipping splay fault on the west limb of the Burning Springs anticline in western West Virginia. Wilson et al (in press) found different orientations of slickensides and other natural fractures in a cored interval above the Pine Mountain thrust than in the thrust zone, deeper in the same core. For these reasons, fracture sys-

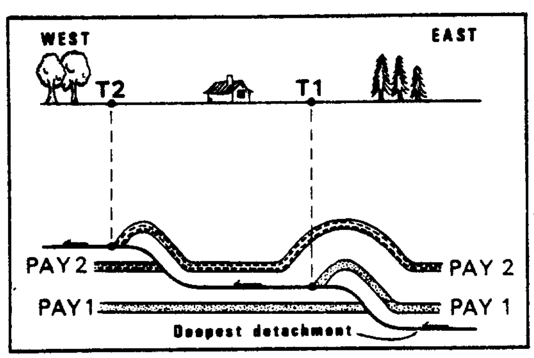

FIG. 6—Schematic cross section of westward limits of advisable drilling for detachment-related fracture zones. To locate detachment-related fracture systems in pay zone 1, one should drill east of *T1*. To locate more fractured rock in the shallower pay zone 2, one may drill as far west as *T2*.

tems observed at ground level are most likely to be direct and simple guides to subsurface fracture zones in a thrust sheet, if any major detachments are in or below the interval of interest.

EXPLORATION STRATEGY

The three structural criteria described (CSD's, short photolineaments, and detachment effects) can be combined to suggest an exploration strategy for gas in structural (fracture) traps in the Devonian shaly rocks of the detached part of the Plateau province of the Allegheny synclinorium (Fig. 7). The strategy may also prove useful for other fractured rocks in this and other overthrust belts.

1. If CSD's in the area of interest are thought to be thrust bounded, wells should be drilled east of the trace of point T2 (Fig. 6) on the ground surface. That trace is the upward projection of the line along which the deepest underlying detachment cuts the top of the interval of interest—the base of the Lower Mississippian Berea Sandstone (Bagnall and Ryan, 1976; Patchen and Larese, 1976; Patchen, 1977). In some areas, most production may be expected from an eastward-thickening interval in the lower part of the Devonian shaly sequence, such as Brown shale zone II of Martin and Nuckols (1976). In such areas, the western limit of recommended drilling moves east, to a line analogous to the trace of point T1 of Figure 6. If the CSD's are considered to have formed over basement faults, wells can be drilled farther west than the traces of T1 and T2.

2. In the area defined by the first criterion, wells should be drilled within the boundaries of a cross-strike structural discontinuity. Examples are the Parsons and Petersburg lineaments in northern West Virginia, the Modoc, White Sulphur Springs, and Covington lineaments in southern West Virginia, and the Tyrone–Mount Union, Everett-Bedford, Mason-Dixon, and McAlevys Fort–Port Matilda lineaments in western and central Pennsylvania (see references listed by Wheeler et al, 1979). Most CSD's now known in the central Appalachians have been found and studied in the eastern Plateau and Valley and Ridge provinces. The westward extent of most CSD's into areas of potential commercial production is feasible but speculative. However, some mapped CSD's correspond with some of the structural lineaments of Rodgers (1963), Gwinn (1964), and Rodgers (1970, Pl. 1A), though not to Woodward's (1968) interruptions in strike. Some of Gwinn's and Rodgers' structural lineaments are in the western Plateau province, so CSD's may also extend that far west. Sites (1978) suggested westward continuation of the Petersburg lineament. Further, many data are now available

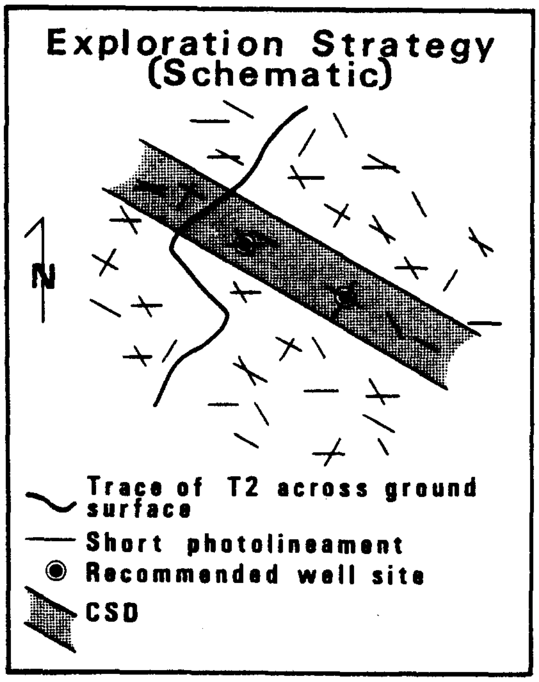

FIG. 7—Exploration strategy (schematic). *T2* is defined in Figure 6.

which may allow CSD's to be extended to the west: well logs, structure contour maps, Landsat images, and maps of residuals from terrane-corrected Bouguer anomalies. Wheeler et al (1976b) suggested that the Parsons structural lineament may be continued westward below the massive and stiff Mississippian and Pennsylvanian rocks, with the thick Middle and Upper Devonian rocks fracturing in stiff sections, and flowing in soft sections to insulate surface structures from reflecting underlying CSD's. However, subsurface and geophysical data like those just listed should permit one to see through any such insulating effect.

3. In the areas defined by the first two criteria, if the four assumptions discussed under "Assumptions" hold, wells should be drilled on intersections of air photo lineaments one to several km long.

CONCLUSIONS

Wells being drilled for gas in fractured Devonian shaly rocks should be sited at intersections of short air photo lineaments, in CSD's. Presence or absence of basement involvement in the CSD's may impose a western limit on such exploration. That exploration strategy is applicable at least as far west as the Mann Mountain anticline in southern West Virginia and the Burning Springs anticline in central West Virginia. Several of the eight partly mapped CSD's in West Virginia and Pennsylvania (Fig. 1) can probably be extended west into the central and western Plateau province. However, because the most important present gas production from Devonian shaly rocks is in the intensely explored area of southwestern West Virginia and eastern Kentucky, where the rocks of interest may not be detached, the conservative form of the exploration strategy presented here may be most useful in exploration of new areas in the detached eastern Plateau province of West Virginia. In Pennsylvania, where CSD's are more clearly basement controlled (Table 1 of Wheeler et al, 1979), the more ambitious form of the strategy of this paper is appropriate.

One or more of the three criteria developed in this paper may be used alone, or may be combined profitably with other methods of predicting locations of structural (fracture) traps. Examples of such possible traps include (1) late-tectonic bed-extending fractures in steeply dipping beds (Berger et al, 1979); (2) stratigraphically confined, porous fracture facies (Shumaker, 1978b); (3) westward propagation of fracturing associated with a CSD, into undetached rocks (Wheeler et al, 1976b); (4) westward propagation of detachment-related fracturing by differential shortening distributed over a vertical interval, west of actual recognizable detachment (Shumaker, 1978a; Wilson et al, in press); (5) fracturing in bottoms of thrust sheets (Harris and Milici, 1977; Milici and Statler, 1978; Wiltschko, 1978b); (6) fractures in footwalls of ramps (Wiltschko, 1978a); (7) upward propagation of anomalously oriented joints or joint zones formed in response to distorted stress trajectories over longitudinal basement faults, such as those bounding the Rome trough in West Virginia (Advani et al, 1978; Kulander et al, 1978; Kulander and Dean, 1978b); (8) fracture-porous CSD's containing gas sealed beneath an overriding thrust sheet (Gold et al, 1978; W. Bagnall, oral and written commun. 1976, 1977), suggested that slickensided faults may seal porous fractures; and (9) bed-extending fractures on anticlinal crests, especially adjacent to a contact with an overlying, much softer, layer (Tapp and Wickham, 1978).

APPENDIX

Types of Data Used to Identify CSD's

Most data types reflect the presence of a CSD as disruptions of, or anomalies in, strike-parallel patterns. The combination of data types that reflect a CSD changes from one CSD to another and along single CSD's, according to data availability and local structure.

1. Bends, ends, or style changes of detached folds or longitudinal thrust faults.[3,4,5]
2. Transverse faults, particularly if movement occurred at more than one time, in more than one direction, or both.[3]
3. High joint intensity: large size, close spacing, or both.[3,4]
4. Presence of some type of small fold or fault that records larger movements.[3,4]
5. Intense cleavage development.
6. Anomalous changes in contours of smoothed values of strike or dip of beds.[3,4]
7. Changes in orientation of structural grain.[3]
8. Gravity anomalies, particularly with terrane corrections.[3,4]
9. Magnetic anomalies, especially if blunt ended.[3]
10. Disruptions in magnetic or gravity gradients.[3]
11. Abrupt changes in depth to magnetic or seismic basement.[3]
12. Earthquake epicenters.
13. Water and wind gaps.[3,4]
14. Course changes of major streams.[3,4]
15. Mineralization: unusually abundant, or indicative of deeply penetrating fracture systems.[3]
16. Volcanic centers and intrusions.
17. Long Landsat photolineaments.[3,4,5]
18. Unusually dense air photo lineaments.[3,4]
19. Facies and thickness changes of stratigraphic units.[3,4]
20. Blocky shapes on isopach maps, indicating abrupt thickness changes across straight lines.[3]
21. Springs: unusual temperatures, chemistries, or yields.[3,4]
22. Gas or oil seeps.[3,4]
23. High or low yields of water or gas wells.[3,4]

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[3]Used in Appalachian overthrust belt of New York State, Pennsylvania, West Virginia, Virginia, and Alabama. In other Appalachian areas, CSD's have apparently not yet been sought systematically.

[4]Used for Parsons or Petersburg lineaments of this paper.

[5]Most widely and effectively used in detecting Appalachian CSD's (Wheeler et al, 1979).

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